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RECENT ADVANCES IN CARDIAC SURGERY[1]

P. GIBSON, F.R.C.S.
Royal Perth Hospital, Western Australia

It is remarkable to reflect that surgery of the heart and great vessels began in earnest only just before the second World War. It is true, however, that for many years prior to this much time and thought had been given to the problems of cardiac surgery and much experimental work had been done. Cardiac wounds had been repaired and foreign bodies had been removed from the heart and pericardium. As long ago as 1925, Henry Souttar, of the London Hospital, reported the first operation was soon confirmed by many patient survived his operation, the value of the surgical relief of mitral stenosis was not appreciated by Mr. Souttar's colleagues, and the operation fell into disfavour.

During the 1930's thoracic surgery in general developed rapidly, and it was at the end of this decade that the first real advance in cardiac surgery came. In 1939, Gross and Hubbard, working in the Children's Hospital in Boston, reported the successful ligation of a patent ductus arteriosus. The practicability of such an operation was soon confirmed by many other workers all over the world. During the war, Harken, also of Boston, although working at the time in Europe, reported successful operations for the removal of foreign bodies from the heart in over 130 cases.

In 1945, Blalock developed a successful operation for the relief (but not cure) of Fallot's tetralogy, the most common cause of a "blue baby". Also in 1945, Crafoord in Sweden and Gross each reported successful operations on patients suffering from coarctation of the aorta (congenital narrowing of a segment of the aorta). They had each been able to excise the narrow segment and restore the continuity of the aorta by end-to-end anastomosis. Three years later, Brock, Harken and Bailey, working independently, and, incidentally, using much the same technique as described by Souttar in 1925, each achieved notable success in the surgical relief of mitral stenosis.

While these advances were being made, much thought was being given to the essential technical problems of operating on the heart. One important fact had become clear, and that was that the heart was not the inordinately sensitive organ it was previously thought to be. Provided it was handled carefully, it could survive surgical incisions, at least in its atria. In conjunction with much experimental data which had by now accrued, this seemed to point to the likelihood that it would not be surgical trauma which would limit the advance of cardiac surgery; more likely it would be the necessity of carrying out this sort of surgery under direct vision.

How could a complicated defect within the heart be repaired under direct vision whilst the heart was always full of blood? It was known that the brain suffered damage if deprived of its blood supply for more than three minutes. Any answer to the problem therefore would need to provide either some means of supplying the rest of the body, and especially the brain, with oxygenated blood during the time the heart was open, or some means of reducing the oxygen needs of the body so that the

[1] Read at a meeting of the Western Australian Branch in 1959

circulation of blood could be stopped for a longer time than three minutes. In fact both of these alternatives have been developed in the last six years and have now been applied to quite large numbers of human cases with considerable success.

PUMP OXYGENATORS

Let us consider the first of these alternatives, that of supplying the rest of the body with blood while the heart itself is excluded from the circulation. It is obvious that if the blood is to be made to bypass the heart completely, then it must also bypass the lungs. In other words, not only must there be a substitute for the heart, but there must also be a substitute for the lungs.

There are two principal functions of the lungs. The first is to add oxygen to the blood passing through them, and the second is to release carbon dioxide from the blood. In the laboratory, if venous blood is exposed to an atmosphere of pure oxygen, its hæmoglobin will absorb oxygen and its plasma will yield carbon dioxide. But the rate at which a given volume of blood can be fully saturated with oxygen depends, amongst other things, on the area of contact between the blood and the oxygen. Thus, the greater the area of the surface of blood in contact with oxygen, the more rapid will be the oxygenation of the blood. One of the practical problems which had to be solved in the development of an efficient oxygenator, then, was that of providing a surface area large enough to oxygenate enough blood to support life.

The problem was solved in several different ways. Gibbon, who began his investigations into this problem before the war, finally solved it by running the blood in a very thin film vertically down a thin stainless steel wire mesh suspended in an atmosphere of oxygen. This eventually proved to be one of the most satisfactory methods of oxygenation, but unfortunately it is one of the most difficult to achieve technically.

Bjork, working in Sweden, experimented with another method of producing a suitably large surface area. His apparatus consisted of a series of discs, like gramophone records, set at close intervals along an axle. The axle was supported horizontally so that the edges of the discs just dipped below the surface of a trough of blood. When the discs were set spinning on the axle at just the right speed, they each became covered with a thin layer of blood. If the whole series of discs were kept in an atmosphere of oxygen, rapid oxygenation took place. This system has been adapted in many ways and the principle is the one which is used in two of the most popular machines in use today, namely, the Kay-Cross machine, which was developed in Cleveland, and the Melrose machine which was developed in London.

The last popular method of oxygenation is by the simple expedient of bubbling oxygen directly into the blood. This had been thought of and tried many years before, but the large quantities of foam produced made it impracticable. In 1954, however, de Wall, Warden, and Lillehei in Minneapolis, made a satisfactory bubble oxygenator in which defoaming was successfully achieved by the use of silicone which was being used widely in the food industry to prevent foaming in certain food manufacturing processes. This indeed became the first oxygenator to be used extensively in clinical practice, and it gained immediate popularity because of its simplicity and because it was so cheap once the actual pumps had been procured. It was made almost entirely of plastic tubing which could be thrown away after being used.

So far I have made little mention of the actual pumps. Whatever sort of oxygenator is used, the oxygenated blood must be pumped back into the patient's systemic arterial system, and the pump must be able to handle quite large volumes of blood—up to four or five litres per minute for an adult—without damaging the blood in any way. Most of the pumps which have been developed for this purpose consist of plastic or latex rubber tubes which are squeezed from one end to the other of a short part of their length.

Let us now see how a patient is connected up to one of these machines so that his heart can be excluded from the circulation of blood through the rest of his body. The heart is widely exposed, either through a bilateral transverse thoracotomy incision, or by a verticle mid-line incision in which the sternum is split throughout its entire length. The pericardial cavity is widely opened, and stout tapes are placed around both the superior and the inferior venæ cavæ. These tapes will later be used as tourniquets to occlude the cavæ completely. A femoral artery is then isolated, and at this stage the patient is given a calculated dose of the anticoagulant, heparin. A catheter is inserted into the femoral artery in the direction of the aorta: it is through this catheter that the oxygented blood will be returned from the pump-oxygenator to the systemic arterial system during the period of bypass. Two cannulæ are inserted through the wall of the right atrium; one is passed up into the superior vena cava and the other is directed downwards into the inferior vena cava. The three cannulæ are then connected to the pump-oxygenator, which previously has been primed with fresh heparinized blood, and the bypass is ready to start. As soon as the clamps occluding the cannulæ in the venæ cavæ are released, blood flows by gravity into the venous reservoir of the pump-oxygenator. From there it is pumped through the oxygenator, and back into the patient's aorta via the femoral artery cannula. As soon as the bypass is proceeding satisfactorily, the tapes are tightened around the cannulæ in the venæ cavæ so that no blood is able to get past them into the heart. The planned operation is then carried out inside the heart and on its completion the bypass is terminated slowly.

Even with this elaborate technique there were still some drawbacks from the point of view of easy operating conditions. Firstly, the heart still had its own considerable blood supply from the aorta via the coronary arteries. The only way to stop this blood from entering the heart and obscuring the operative field is to place a clamp across the aorta above the origin of the coronaries. Secondly, even though deprived of blood by venous occlusion, the heart continues to beat, and so provides the surgeon with a moving target to operate upon. It was then found by Melrose and his colleagues that if a dose of potassium citrate is injected into the coronary arteries and the flow of blood through the coronaries then stopped by placing a clamp on the aorta as described above, the heart at once becomes completely paralysed, and stays paralysed until blood is allowed to course down the coronaries again and wash the potassium out of the heart. The use of potassium in this way for producing a completely quiet heart has greatly facilitated the performance of delicate manœuvres inside the heart.

These techniques have now been in use in many parts of the world since 1955 for the correction of a wide variety of congenical and acquired heart lesions. Particularly good results have been obtained in the correction of atrial septal defects and ventricular septal defects, and promising results have been reported in many other conditions. Unfortunately the complete correction of Fallot's tetralogy has proved disappointing, being attended by an operative mortality of about 30%, even in the best hands.

REDUCING THE OXYGEN NEEDS OF THE BODY: HYPOTHERMIA

For a long time it has been known that normal body metabolism is depressed at low temperatures. The question of artificially lowering the body temperature on non-hibernating animals was studied experimentally by Bigelow in Canada. As was expected, it was confirmed that the oxygen consumption could be reduced considerably by means of hypothermia, and further experiments were soon under way to determine just how long a brain may be deprived of blood at low temperatures without suffering any detectable damage. At first this seemed to be extremely encouraging, and it was shown that the more the body temperature was lowered, the longer the brain could be deprived of oxygen.

Then came the big snag of hypothermia. It was found that if the heart is cooled to a temperature of between 25 and 30° C., it becomes very irritable and often develops a disordered heart beat known as ventricular fibrillation. When this happens, instead of the ventricles contracting regularly and in unison, individual groups of muscle fibres contract independently of each other. Thus there is no coordinated beat and no ejection of blood from the heart, so that the circulation comes to a standstill. If ventricular fibrillation occurs at normal temperatures and is treated at once by cardiac massage and defibrillation by means of an electric shock, normal rhythm can usually be reestablished without much difficulty. When it occurred at these low temperatures, however, it was usually very difficult to reestablish a normal rhythm. It soon became clear that the risks of taking the body temperature of man down to levels much below 29° C. were too great to warrant the procedure being used, especially if the heart was being handled

However, temperatures down to 30° C. were found to be perfectly safe, and at this temperature the cerebral circulation could be occluded for eight clear minutes. This is sufficient time to allow the surgical closure of simple atrial septel defects, and the relief of pulmonary and aortic valve stenoses. Especially in Britain, where the development of pump-oxygenators has been rather slower than in the U.S.A., hypothermia has become the standard technique to allow the repair of these lesions.

There are three ways of lowering the body temperature to 30° C. in current use. In all three methods the actual cooling is not commenced until the patient has been anæsthetized in the usual way. Perhaps the most common method is to place the anæsthetized patient in a tub of iced water until the body temperature (measured by a thermometer in the œsophagus) is reduced to about 31 to 32° C. The patient is then removed from the bath and thoroughly dried before being placed on the operating table. The temperature will continue to fall another one or two degrees, depending on the size and obesity of the patient, and will then remain steady for a few hours or until the anæsthetic is lightened.

In the second method, the patient is wrapped in a double thickness of rubber blanket, and iced water is circulated between the two layers of the blanket until the desired temperature is reached. This method has the advantage of being less messy than the previous one, but has the decided disadvantage of taking a longer time to obtain a satisfactory fall in temperature.

In the third method, some of the patient's blood is pumped through a plastic tube immersed in iced water or some other cooling fluid. Having been so cooled, the blood is then returned to the patient.

The actual surgery is carried out in much the same way as bypass surgery. After adequate exposure of the heart the venæ cavæ are surrounded by tapes. The site of the incision in the heart is then prepared, a clamp is applied to a lip of the atrial or vessel wall and the incision is made in this lip before the circulation is occluded. The tapes around the venæ cavæ are then tightened. The heart is allowed to beat for a few seconds to empty itself of blood. The clamp is then removed and the previously made incision opened up. When the surgical procedure inside the heart is completed, the tapes on the venæ cavæ are loosened, and as soon as the heart is full of blood again the clamp is reapplied.

More recently, body temperature has been reduced to much lower levels by the combination of hypothermia and an artificially supported circulation. If the heart is bypassed and the circulation maintained while the actual cooling takes place, then clearly it does not matter what sort of irregular rhythm the heart has, provided it can be restored to normal rhythm at the end of the rewarming period.

During the last few years, much work has been done in America using a pump oxygenator and a "heat exchanger" to lower the body temperatures of experimental animals to very low levels. This work was continued and extended in England by Kenyon and his colleagues, who recently reported a series of experimental animals whose temperatures were taken down to between 5 and 10° C. by these means. At this low temperature the circulation was occluded for some 45 to 60 minutes before rewarming was commenced. Out of ten such animals, eight survived to make uneventful recoveries.

At the same time, also in England, Drew and his colleagues developed a slightly different method of inducing profound hypothermia, and earlier this year published the results of a series of experiments and a small number of clinical cases using their method. The method consisted of bypassing each side of the heart separately, cooling the blood in a heat exchanger before returning it to the patient, and using the patient's own lungs as an oxygenator.

These patients of Drew's constitute the first published series of cases in whom this exciting new technique has been used. The report has triggered off a wave of enthusiastic investigation into the use of the method in many parts of the world. Already many of the physiological problems have been worked out, although much still remains to be done before it becomes as established a part of cardiac surgery as ordinary hypothermia or the well-tried pump-oxygenator techniques. The big practical advantage of profound hypothermia is that at the time the actual surgery is being carried out on the heart itself, there is absolutely nothing else happening—there is no circulation, no respiration, no cardiac action apart from an occasional beat, and above all there is no haste on the part of the surgeon.

I have mentioned this technique of "profound hypothermia", which is still largely in the experimental stage, not only because it seems to represent yet another step forward in the development of safer cardiac surgery, but also because it emphasizes that progress is still being made. Indeed, one may safely say that despite the enormous strides that have been made in the last five years, cardiac surgery is still very much in its infancy and the future holds a certain promise of even more startling developments.